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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 5 : H04B 10/12, 10/14	A1	(11) International Publication Number: WO 91/18455 (43) International Publication Date: 28 November 1991 (28.11.91)

(21) International Application Number: PCT/IT91/00036

(22) International Filing Date: 6 May 1991 (06.05.91)

(30) Priority data:
47949/A/90 11 May 1990 (11.05.90) IT

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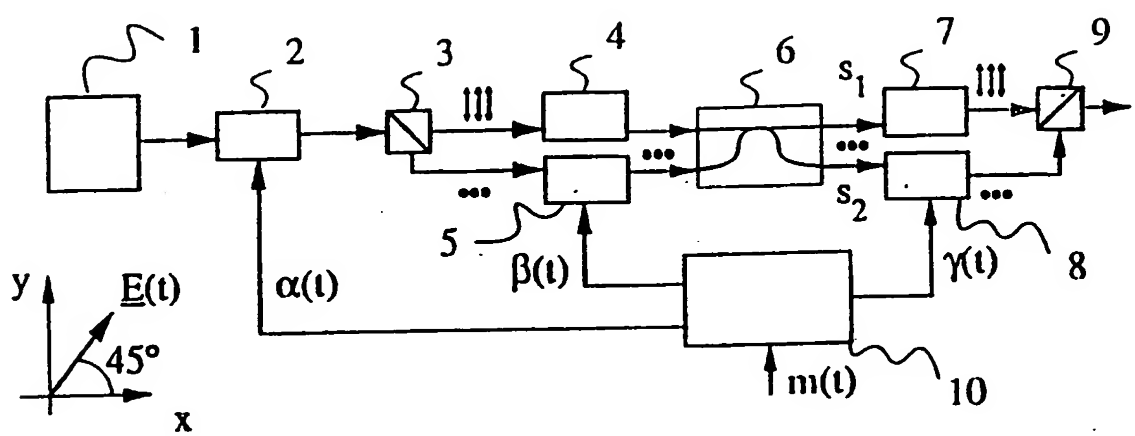
(81) Designated States: AT (European patent), AU, BB, BE (European patent), BF (OAPI patent), BG, BJ (OAPI patent), BR, CA, CF (OAPI patent), CG (OAPI patent), CH (European patent), CI (OAPI patent), CM (OAPI patent), DE (European patent), DK (European patent), ES (European patent), FI, FR (European patent), GA (OAPI patent), GB (European patent), GR (European patent), HU, IT (European patent), JP, KP, KR, LK, LU (European patent), MC, MG, ML (OAPI patent), MR (OAPI patent), MW, NL (European patent), NO, PL, RO, SD, SE (European patent), SN (OAPI patent), SU, TD (OAPI patent), TG (OAPI patent), US.

Published
With international search report.

(54) Title: A MULTILEVEL COHERENT OPTICAL SYSTEM



(57) Abstract

A multilevel coherent optical system is disclosed in which a multilevel signal with a coherent optical carrier is provided by means of a modulation of the phase and the polarization of the electromagnetic field propagating through a single-mode optical fibre, a heterodyne transmitter and receiver for said signal being also disclosed. The transmitter comprises a coherent light source (1) providing the optical carrier, a phase modulator (2) modulating the phase of the carrier, a polarization modulator (3-8), and a modulation signal generator (10) providing control signals to the phase modulator (2) and the polarization modulator. The receiver comprises a first stage (12-23) carrying out the heterodyne detection of the phase component and the phase quadrature component of the polarization of the signal received through an optical fibre (11), a second stage demodulating the received signal to provide the multilevel signal, and a processing circuit comparing the received multilevel signal with predetermined reference signals. Such a system exploits the four degrees of freedom of the electromagnetic field propagating through the optical fibre so as to approach closer to the theoretical Shannon limit than conventional systems.

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A MULTILEVEL COHERENT OPTICAL SYSTEM

The present invention relates to the communication systems using optical signals propagating through single-mode optical fibres and, in particular, a method of and an apparatus for generating, transmitting and receiving a multilevel optical signal.

Reliable and economically competitive, coherent optical transmission systems which can be made available at short and medium terms allow novel network architectures to be provided regarding long-distance and high-performance connections and multi-user LAN (Local Area Network) and MAN (Metropolitan Area Network) connections as well. In particular, the very large bandwidth of the single-mode optical fibres (thousands of GHz) can be suitably exploited by providing optical FDM-systems (Frequency Division Multiplexing) in which the selection of the desired channel can be obtained by shifting the frequency of the local oscillator. This allows passive optical networks with very high traffic capacity (thousands of gB/s) to be carried out. However, two important aspects restrict on one hand the bandwidth of the single channel and limit on the other hand the maximum number of channels which can be tuned by the user. In the first instance, in fact, the main restriction is due to the bandwidth of the photodiodes and the electronic circuits, while regarding the second instance it should be considered that the frequency range which can be tuned by the user depends on the tunability characteristics of the laser used as local oscillator.

In order to increase the information rate of any channel, systems have been provided in which the information to be transmitted is coded with more than two levels instead of being coded using only the two binary levels as it is customary for providing a high signal reception sensitivity. By transmitting multilevel signals an improvement of spectrum efficiency expressed in terms of information rate per unit of occupied band is obtained at the cost of a reduction of the sensitivity. The known systems with two or more levels resort to the digital amplitude and phase keying (APK) or to the digital phase shift keying (PSK) or polarization shift keying (SPSK) of the electrical component of the electromagnetic field associated to a coherent optical wave generated by a laser source.

The present invention seeks to provide a method of generating a multilevel signal with a better performance than the known systems with regard to the signal reception sensitivity on the same number of employed levels.
Within such general aim the invention seeks to provide in particular a transmitting and a receiving apparatus carrying out the above mentioned method.

Such aims are achieved by the invention defined and characterized in general in the claims attached to the following description in which the present invention is disclosed by way of a non-limitative example with reference to the accompanying drawing, in which:
Fig. 1 is a block diagram of a transmitting apparatus for a multilevel optical signal according to the present in-

vention;

Fig. 2 is a block diagram of the detecting stage and the intermediate frequency stage of a receiving apparatus according to the invention;

Fig. 3 is a block diagram of a multilevel signal processing stage based on the determination of the coefficients of the inverted Jones matrix in a receiving apparatus according to the invention;

Fig. 4 is a block diagram of a multilevel signal processing stage based upon an algorithm for providing and uptodating the values of the components of the reference vectors in the receiving apparatus of the invention;

Fig. 5 is a block diagram of the circuit of the stage of Fig. 4 for uptodating the values of the components of the reference vectors;

Fig. 6 is a diagram of the logarithm of the error probability P_e versus the number of the received photons per bit F for different values of the level number N;

Fig. 7 is a graph for the comparison of the sensitivity of the receiving apparatus (N-4Q) according to the invention, expressed in terms of the logarithm of the number of received photons per bit F versus the level number N, with the sensitivity of a N-PSK apparatus (N-level Phase Shift Keying), a N-APK apparatus (N-level Amplitude and Phase Keying), and a N-SPSK apparatus (N-level Polarization Shift Keying with detection by Stokes parameters); and

Fig. 8 is a graph for the comparison of the sensitivity of the receiving apparatus according to the invention, expressed in terms of the logarithm of the number of received photons per bit F versus the level number N,

with the limit performance of the transmitting apparatus defined by the Shannon expression of the transmitting channel capacity.

The electrical field $\underline{E}(t)$ of an electromagnetic wave having angular frequency ω_o and propagating through a single-mode optical fibre can be written as follows:

$$\underline{E}(t) = E_x(t)\underline{x} + E_y(t)\underline{y} = (x_1+ix_2)\underline{x} + (x_3+ix_4)\underline{y}\ e^{i\omega_o t}$$

where the phase terms x_1 and x_3 and the phase quadrature terms x_2 and x_4 are the components on the reference axes $\underline{x}$ and $\underline{y}$ of the polarization state, i.e. the vector representing the electrical field according to a given polarization. Vector $X = (x_1, x_2, x_3, x_4)$ can be associated to any state of such electromagnetic field, the components of which being such that:

$$x_1^2 + x_2^2 + x_3^2 + x_4^2 = P$$

where P is the transmitted optical power;

The schematic block diagram of a transmitter according to the invention is shown in Fig. 1: a laser source 1 generates a linearly polarized optical carrier having a frequency, for example, of 10^{14} Hz, so as to form an angle of 45° with respect to the reference axes $\underline{x}$ and $\underline{y}$. The phase of such optical field is modulated by a phase modulator 2 with a message, for example a voltage having a time variable amplitude $\alpha(t)$, which is generated by a coder 10 from a binary sequence m(t) representing an information to be transmitted. After the phase modulation the components of the polarization state on axes $\underline{x}$ and $\underline{y}$ are split by a polarization selection beam splitter 3. It should be noted that the reference axes $\underline{x}$ and $\underline{y}$ are defined by the orientation of splitter 3. In the upper

branch the polarization of the signal is rotated by 90° by a polarization rotator 4 so as to align it with that of the signal in the lower branch. The phase of the latter signal is modulated by a modulator 5 with a message $\beta(t)$ also generated by coder 10. The two signals having the same polarization are mixed by a directional coupler 6, the outputs of which will be as follows:

$$s_1(t) = A/2\ e^{i[\omega_o t + \alpha(t)]}\left[e^{i\beta(t)} + e^{i\pi/2}\right]$$

$$s_2(t) = A/2\ e^{i[\omega_o t + \alpha(t)]}\left[e^{i\beta(t)+i\pi/2} + 1\right]$$

where A^2 is proportional to the transmitted optical power. The polarization state of signal s_1 is then rotated by 90° by a polarization rotator 7 so as to make it orthogonal to that of signal s_2, the phase of which is modulated by a modulator 8 with a message $\gamma(t)$ generated by coder 10. The resulting signals are then coupled by a polarization selection directional coupler 9 to provide the optical signal to be transmitted through the fibre, the x and y polarization components of which have the following phase terms and phase quadrature terms:

$$x_1 = A\cos[\beta(t)/2 + \pi/4]\ \{\cos[\alpha(t) + \beta(t)/2 + \pi/4]\cos\gamma(t) + -\sin[\alpha(t) + \beta(t)/2 + \pi/4]\sin\gamma(t)\}$$

$$x_2 = A\cos[\beta(t)/2 + \pi/4]\ \{\cos[\alpha(t) + \beta(t)/2 + \pi/4\ \sin\gamma(t) + -\sin[\alpha(t) + \beta(t)/2 + \pi/4\ \cos\gamma(t)\}$$

$$x_3 = A\sin[\beta(t)/2 + \pi/4\ \ \cos[\alpha(t) + \beta(t)/2 + \pi/4]$$

$$x_4 = A\sin[\beta(t)/2 + \pi/4\ \ \sin[\alpha(t) + \beta(t)/2 + \pi/4]$$

where the function $\alpha(t)$, $\beta(t)$ and $\gamma(t)$ can have values between 0 and 2π according to the selected codification method.

In particular, such functions are generated by coder 10 according to the following criteria. A succession of bits representing the information to be transmitted are fed

into coder 10. Such succession is divided in groups of bits, each group of bits representing a symbol of the alphabet used by the coder. Thus the succession of bits is transformed in a succession of symbols. In case a N-level signal is transmitted and, for the sake of semplicity, under the assumption that N is a power of 2, each symbol is formed by m bits where m = 2 log N. Each symbol can be univocally associated to a point of the sphere in the four-dimensional space in which the electromagnetic field is represented, such point being determined by the vector $\underline{X} = (x_1, x_2, x_3, x_4)$ or by a tern of generalized spherical coordinates α, β and γ and by the radius of the sphere, i.e. the square root of the transmitted optical power. Therefore, the transmission of a symbol corresponds to the transmission of a well defined state of the electrical field. As the succession of bits m(t) are fed into the coder, an association between symbols and points at the coordinates α, β and γ is effected; the latter are then entered into a digital-to -analog converter and transformed to the voltages $\alpha(t)$, $\beta(t)$ and $\gamma(t)$ which are the control signals of the demodulators 2, 5 and 8. It should be noted that the states of the electrical field are completely determined by the three angular coordinates as the transmitted optical power in the apparatus of Fig. 1 remains constant.

The block diagram of the stage detecting the optical signal and of the intermediate frequency stage of a receiving apparatus according to the invention is shown in Fig. 2.

The optical signal modulated in phase and polarization and generated by a transmitter of the type shown in Fig.

1 and transmitted through a single-mode fibre 11 is entered into a "90° optical hybrid" 13 along with a coherent optical signal generated by a laser source operating as local oscillator 12. Such signal of the local oscillator having a frequency which differs from that of the transmitted signal carrier by a predetermined amount between 10^8 and 10^9 Hz is linearly polarized at 45° with respect to the reference axes x and y. The 90° optical hybrid 13 is a known device having two inputs and two outputs and providing at one output the sum of the input signals and at the other output the sum of one input signal and the other input signal the phase of which is shifted by 90°. In such a case, therefore, the output signals are the phase component and the phase quadrature component of the beat signal.

The x and y components of the polarization state of the output signals of the optical hybrid 13 are then split by polarization selection beam splitters 14 and 15 defining with their orientations the reference axes x and y, and separately detected by four photodiodes 16, 17, 18 and 19. The four electrical intermediate frequency signals are then filtered by bandpass filters 20, 21, 22 and 23 centered about the intermediate frequency and having a double as high bandwidth as the figure rate R_s, i.e. the inverse of the transmission time of a symbol. A phase locked loop (PLL) 28 and four multipliers 24, 25, 26 and 27 allow the four intermediate frequency signals y_1, y_2, y_3 and y_4 at the outputs of the filters 20-23 to be translated to base band. Such signals are then fed to four lowpass filters 29, 30, 31 and 32 having the same bandwidth as the figure rate R_s so as to provide four

base band signals z_1, z_2, z_3 and z_4 proportional to the estimated values of the components of vector $\underline{X}$ which are mainly impaired by the detection noise.

Two preferred embodiment of the processing apparatus have been proposed for providing and uptodating the estimated values of the components of vector $\underline{X}$ from the base band signals z_1, z_2, z_3 and z_4. Such apparatus allow the fluctuations of the polarization state of the optical signal due to the propagation through a single-mode fibre to be compensated by merely electronic techniques.

The operation of the first apparatus, the block diagram of which is shown in Fig. 3, is based on the determination of the inverse Jones matrix. As it is known, the effects due to the propagation through a single-mode optical fibre can be taken into account by the Jones unit operator providing the input-output relation between the polarization states of the optical field. Since such relation is linear, the application of the inverse Jones operator to the received signal allows the polarization state of the transmitted optical signal to be determined. Vector $\underline{Z}$ having the base band signals z_1, z_2, z_3 and z_4 as components is multiplied in block 33 by the inverse Jones matrix so as to provide the estimated values of the components of vector $\underline{X}$. The coefficients of the matrix are determined by an algorithm based upon the consideration that the fluctuations of the polarization state (0,1-1 Hz) due to the fibre birefringence are much slower than the figure rate (10-1000 Hz). The algorithm is implemented on the base of the calculation of the time averages of the signals z_1, z_2, z_3 and z_4 at blocks 34,

35, 36 and 37 in time intervals much longer than the symbol period, i.e. the transmission time of a symbol, and much shorter than the characteristic period of the polarization fluctuations. The elements of the Jones matrix depend linearly on the averages of the signals z_1, z_2, z_3 and z_4, as the coefficients of such linear relation are the averages of the four coordinates of the reference points evaluated in the set of the N feasible transmitted symbols and stored in block 38. Therefore, if the averages of the signals z_1, z_2, z_3, z_4 are known, a linear system of four equations with four unknown values can be implemented, the solution of which calculated in block 38 provides the real and imaginary parts of the coefficients of the Jones matrix, the inverse of which is then calculated in block 33. This algorithm causes the coefficients of the Jones matrix to be uptodated at the end of any time period at which the time averages of the signals z_1, z_2, z_3 and z_4 are evaluated, thus allowing the apparatus to follow the fluctuations of the polarization state due to the single-mode fibre birefringence. The decision, i.e. the recognition of the state of the multilevel signal received at a given time, is effected in block 39 by comparing the estimated vector ε of components ε_1, ε_2, ε_3 and ε_4 with the reference vectors corresponding to the feasible transmitted symbols, the components of which have been stored in block 39 when adjusting the apparatus. In particular, such comparison is effected by calculating the distances between the point on the surface of the sphere in the four-dimensional space corresponding to the estimated vector ε and the points determined by the reference vectors. Among the

feasible transmitted symbols it is selected the symbol corresponding to the point determined by the reference vector having the shortest distance from the point of coordinates $\mathcal{E}_1$, $\mathcal{E}_2$, $\mathcal{E}_3$ and $\mathcal{E}_4$. The output signal of block 30 is fed to an user apparatus 50.

The operation of the second apparatus processing the multilevel signal is on the contrary based upon an algorithm allowing the values of the coordinates of the reference points to be initially determined and uptodated, i.e. the components of the reference vectors on the surface of the sphere in the four-dimensional Euclidean space. The schematic block diagram of such processing apparatus is shown in Fig. 4. The apparatus determines initially the reference vectors by means of a suitable initialization sequence and subsequently effects the continuous uptodating of the components of such vectors, the values of which are fed to block 45 in which a decision is taken by the above described procedure based upon the calculation of the distance between the point corresponding to the received symbol and the reference points. The decision circuit 45 in case of a N-level signal has 4N memory cells in which the components of the N reference vectors are stored. In the time interval between two successive uptodatings the decision circuit 45 estimates the received symbol and associates it to any of the N symbols which can be transmitted. The uptodating of the components of any reference vector is carried out by calculating the mean value of the vector components which are estimated by the decision circuit during the uptodating interval as corresponding to that reference vector. At the end of any uptodating interval,

which is chosen also in this case much shorter than the characteristic periods of the polarization fluctuations and much longer than the symbol period, the reference vectors are replaced by those corresponding to the novel components, the mean values of which calculated by the above described method have been stored in the 4N memory cells.

In the diagram of Fig. 4 the uptodating operation is effected by means of block 40 formed of four circuits 41, 42, 43 and 44, each of them comprises a switch 46 and N circuits 47 for the calculation of the mean value of the signal selected by the switch. After having estimated the received symbol, the decision circuit 45 supplies the control signal formed of the components of the reference vector corresponding thereto to the four blocks 41, 42, 43 and 44. Such control signal causes any base band signal z_1, z_2, z_3 and z_4 to be entered through switch 46 into circuit 47 for the calculation of the mean value corresponding to the reference symbol selected by the decision circuit 45 among the N feasible symbols which can be transmitted. Therefore, during the uptodating interval the outputs of the circuits 41, 42, 43 and 44 supply the signals which are to be used at the uptodating time to calculate the mean values of the components of the novel reference vectors which are then stored in the 4N memory cells of the decision circuit 45. The resulting processing signal of block 45 is supplied to an user apparatus 50.

The performance of the apparatus has been valued in view of the statistics of the detection noise. In order to optimize the performance, the reference states of the

transmitted optical field have been selected such as to reduce to a minimum the optical power necessary to achieve a predetermined error probability. In case of a N-level signal such choise consists in determining the position of N reference points on the sphere of the four-dimensional Euclidean space. From an analytical point of view the optimization of the performance can be achieved by an algorithm which minimizes the multi-variable function establishing the relationship between the error probability P_e and the coordinates of the N reference points. The problem cannot be analytically solved in closed form so that a numeric algorithm has been used to minimize the above mentioned multi-dimensional function for $3 \leq N \leq 32$.

Some results regarding feasible configurations of N reference points obtained by the minimization algorithm of multi-variable functions and using the downhill simplex method are shown in the following tables I, II, III, IV.

Table I

Level	φ°	ψ°	θ°
1	0.00	0.00	0.00
2	182.65	75.52	0.00
3	117.70	124.54	161.56
4	157.16	308.49	295.89
5	298.07	310.91	144.30

Table II

Level / Level	1	2	3	4	5
1	0.000	1.581	1.581	1.581	1.581
2	1.581	0.000	1.581	1.581	1.581
3	1.581	1.581	0.000	1.581	1.581
4	1.581	1.581	1.581	0.000	1.581
5	1.581	1.581	1.581	1.581	0.000

Table III

Level	$\phi°$	$\psi°$	$\theta°$
1	0.00	0.00	0.00
2	180.00	0.00	0.00
3	57.43	90.00	0.00
4	113.52	2.43	90.00
5	212.56	270.00	0.00
6	122.57	270.00	180.00
7	211.76	332.02	270.00
8	327.42	90.00	180.00

Table IV

Level \ Level	1	2	3	4	5	6	7	8
1	0.000	2.000	1.414	1.414	1.414	1.414	1.414	1.414
2	2.000	0.000	1.414	1.414	1.414	1.414	1.414	1.414
3	1.414	1.414	0.000	1.414	1.414	2.000	1.414	1.414
4	1.414	1.414	1.414	0.000	1.414	1.414	2.000	1.414
5	1.414	1.414	1.414	1.414	0.000	1.414	1.414	2.000
6	1.414	1.414	2.000	1.414	1.414	0.000	1.414	1.414
7	1.414	1.414	1.414	2.000	1.414	1.414	0.000	1.414
8	1.414	1.414	1.414	1.414	2.000	1.414	1.414	0.000

In particular Table I shows the values of the angular coordinates ϕ, ψ and θ corresponding to the points of the sphere of the four-dimensional Euclidean space having standardized unit radius which are associated to the reference states of the electromagnetic field in case of an optimized five-level configuration. The angular coordinates are bound to the components x_1, x_2, x_3 and x_4 defining the state of the electromagnetic field by the following relations:

$$x_1 = \cos\phi\cos\psi\cos\theta$$
$$x_2 = \cos\phi\cos\psi\sin\theta$$
$$x_3 = \cos\phi\sin\psi$$
$$x_4 = \sin\phi$$

Table II shows the values of the distances between the reference points on the sphere of standardized unit radius in case of a five-level configuration; in this case the distance of any couple of points is the same, and when that result is obtained, that is the best for simmetry reasons.

Table III shows the values of the angular coordinates ϕ, ψ and θ corresponding to the points on the sphere of the four-dimensional Euclidean space having standardized unit radius which are associated to the states of the electromagnetic field in case of an eight-level configuration.

Table IV shows the values of the distances between the reference points on the sphere having standardized unit radius in case of an eight-level configuration. In such case it was not possible to arrange the eight reference points on the four-dimensional sphere in such a way that they are at the same distance from one another. Never-

theless the optimum configuration has a high simmetry as any point has six first near points at a distance equal to the radius of the sphere multiplied by $\sqrt{2}$ and only one second near point at a double as high distance as the radius of the sphere.

In Fig. 6 the performance of the apparatus is shown by the logarithm of the error probability P_e versus the photon number per bit F for a number N of levels equal to 4,8 and 16, respectively.

In Fig. 7 the sensitivity of the apparatus is shown by the logarithm of the photon number per bit versus the number N of levels at an error probability of 10^{-9}. In such figure the performance of the apparatus according to the invention designated by N-4Q is compared with that of a N-level heterodyne PSK apparatus (N-PSK, N-Phase-Shift-Keying), a N-level heterodyne APK apparatus (N-APK, N-Amplitude-Phase-Keying), and a N-level polarization modulation apparatus with detection by Stokes parameters (N-SPSK, N-Stokes-Parameter-Shift-Keying), the former two being described in K. Feher "Digital MODEM Techniques", Advanced Digital Communications, Prentice-Hall Inc., Eaglewood Cliffs, New Jersey, 1987, the third one being described in an article of S. Betti, F. Curti, G. De Marchis, E. Iannone, "Multilevel Coherent Optical System Based On Stokes Parameters Modulation" which is being published on the Journal of Lightwave Technology.

In Fig. 8 the limit performance of the transmitting apparatus conditioned by the Shannon equation regarding the channel capacity is shown. The apparatus according to the invention suffers from a penalty with respect to the Shannon limit of 8.5 dB for N = 16, 7.4 dB for N = 32 and

7.8 dB for N = 64, respectively. The performance of the apparatus according to the invention with respect to the compared apparatus tends to improve as the number of levels increases as illustrated in the following Table V showing the improvement in dB of the performance of the apparatus according to the invention with respect to that of N-SPSK and N-PSK apparatus.

TABLE V

N	N-SPSK	N-PSK
8	1.4	3.8
16	2.3	5.4
32	3.0	9.3
64	3.8	10.9

While only one embodiment of the invention has been illustrated and described, it should be appreciated that several changes and modifications can be made without parting from the scope of the invention.

CLAIMS

1. A method of providing a multilevel signal on a coherent optical carrier in order to transmit information through a single-mode optical fibre by the modulation of the carrier, characterized in that the phase and the polarization of the carrier are modulated.

2. The method of claim 1, characterized by the following steps:

-modulating the phase of the carrier with a first control signal;

-dividing the carrier the phase of which is modulated in two orthogonal components representing the polarization state; and

-modulating the phase of said orthogonal components by a second and a third control signals;

said control signals being provided by coding a binary succession representing the information to be transmitted and formed of a plurality of symbols, each of them representing a predetermined state of the multilevel signal to be transmitted.

3. The method of claim 2, characterized in that the predetermined states of the multilevel signal to be transmitted, each represented by the components of a four-dimensional vector defining a reference point on the surface of the sphere of the four-dimensional Euclidean space having a radius equal to the square root of the transmitted optical mean power, are determined by selecting the respective reference points such as to minimize the multi-variable function correlating the bit error probability with the coordinates of said reference points.

4. An apparatus for the transmission of multilevel signals formed according to the method of claim 1, comprising a coherent light source (1) adapted to generate the optical carrier and a modulation signal generator (10), characterized in that it is further comprised of a first phase modulator (2) adapted to modulate the phase of said carrier, and a polarization modulator (3-8) coupled to the output of the first phase modulator (2), and the modulation signal generator (10) has an output connected to the first phase modulator (2) and at least one output connected to the polarization modulator (3-8) to provide thereto phase and polarization modulation control signals.

5. The transmitting apparatus of claim 4 for carrying out the method according to claim 2 or 3, characterized in that between the first phase modulator (2) and the polarization modulator (3-8) a polarization selection beam splitter (3) is connected which is adapted to split the two orthogonal components of the polarization state of the carrier, and that the polarization modulator (3-8) comprises a polarization rotator (4) rotating by 90° the polarization of one of such components, a second phase modulator (5) adapted to modulate the phase of the other component, a 2x2 directional coupler (6) supplying to the output ports the superimposed input signals, a second polarization rotator (7) rotating by 90° the polarization of one of the two input signals of the directional coupler (6), and that the modulation signal generator (10) comprises a coder (10) supplying from the binary sequence the control signals to the three phase modulators (2, 5, 8), and that the output of the polarization

modulator (3-8) is connected to a polarization selection directional coupler (9) for combining again the orthogonal components of the polarization state and for entering the obtained signal into the optical single-mode fibre (11) acting as transmission channel.

6. An apparatus for receiving multilevel signals formed according to the method of claim 1, characterized in that it comprises a first stage (12-23) coupled to the optical fibre (11) and adapted to carry out the heterodyne detection of the phase terms and the phase quadrature terms of the orthogonal components of the polarized signal received by the optical fibre (11), a second stage coupled to the first stage and adapted to demodulate the received signal for providing the multilevel signal, and a processing circuit adapted to compare said multilevel signal with predetermined reference signals.

7. The apparatus of claim 6 for receiving multilevel signals formed according to the method of claim 2 or 3, characterized in that the first stage comprises a 90° optical hybrid (13), an optical local oscillator (12), two separators (14, 15) of the orthogonal polarization components of the phase terms and phase quadrature terms of the beat signal, four photodiodes (16-19) for the detection of said signals, and four bandpass filters (20-23) centered about the intermediate frequency, and that the second stage (24-32) comprises an electronic device for converting to base band the intermediate frequency signals and comprising a phase locked loop (28), four multipliers (24-27) and four bandpass filters (29-32), and that the processing circuit based upon the evaluation of the inverse Jones matrix comprises four

circuits (34-37) receiving at their inputs the base band signals from the bandpass filters (29-32), calculating the time averages of said signals in time periods much longer than the symbol period and much shorter than the characteristic periods of the polarization fluctuations, and supplying at their outputs four signals representing said time averages, a circuit for the inversion of the Jones matrix (33) receiving at its input the above mentioned base band signals and supplying at its output the estimated values of the transmitted multilevel signal, a calculation circuit (38) receiving at its input the four signals representing the time averages of the base band signals and comparing said signals with the feasible transmitted symbols forming the predetermined reference signals stored in the circuit itself so as to calculate the coefficients of the Jones matrix and to supply them to the circuit for entering the Jones matrix (33), and a decision circuit (39) receiving at its input the estimated values of the transmitted multilevel signal and comparing said values with the feasible transmitted symbols stored in the circuit itself so as to assign to each estimated value one of the feasible transmitted symbols.

8. The apparatus of claim 6 for receiving multilevel signals formed according to the method of claim 2 or 3, characterized in that the first stage comprises a 90° optical hybrid (13), an optical local oscillator (12), two splitters (14, 15) of the orthogonal polarization components of the phase terms and the phase quadrature terms of the beat signal, four photodiodes (16-19) for the detection of said signals, and four bandpass filters

(20-23) centered about the intermediate frequency, and that the second stage (24-32) comprises an electronic device converting to base band the intermediate frequency signals and formed of a phase locked loop (28), four multipliers (24-27) and four bandpass filters (29-32), and that the processing circuit comprises first circuit means (45) for determining initially the reference signals by an initialization sequence, second circuit means (40) adapted to calculate the time average of the base band signals in time periods much longer than the symbol period and much shorter than the characteristic period of the polarization state fluctuations, and to store and to uptodate the components of the reference signals, the decision circuit means (45) being adapted to compare the time averages of the base band signals with the reference signals and to assign to each of them one of the feasible transmitted symbols, the uptodating time period being much shorter than the characteristic period of the polarization fluctuations and much longer than the symbol period.

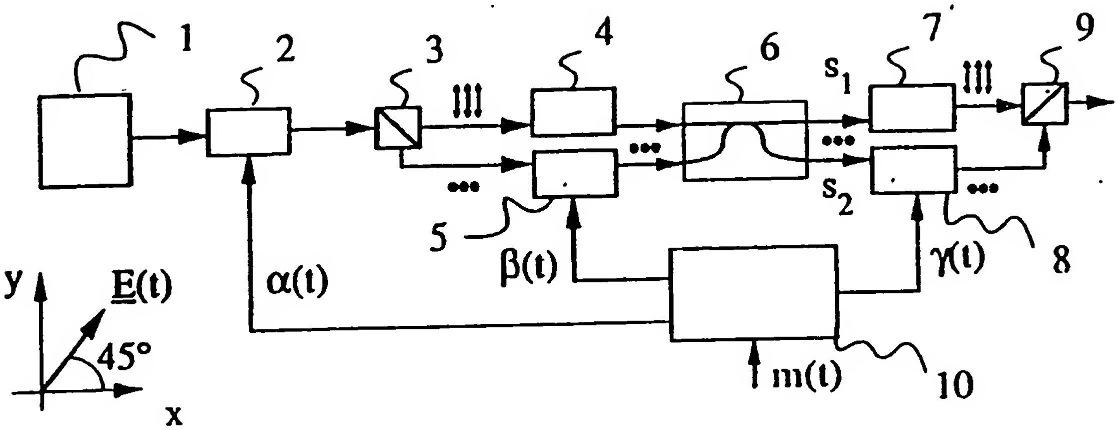
1
2
3
4
5
6
7
8
9
10
s_1
s_2
α(t)
β(t)
γ(t)
m(t)
y
x
E(t)
45°

Fig. 1

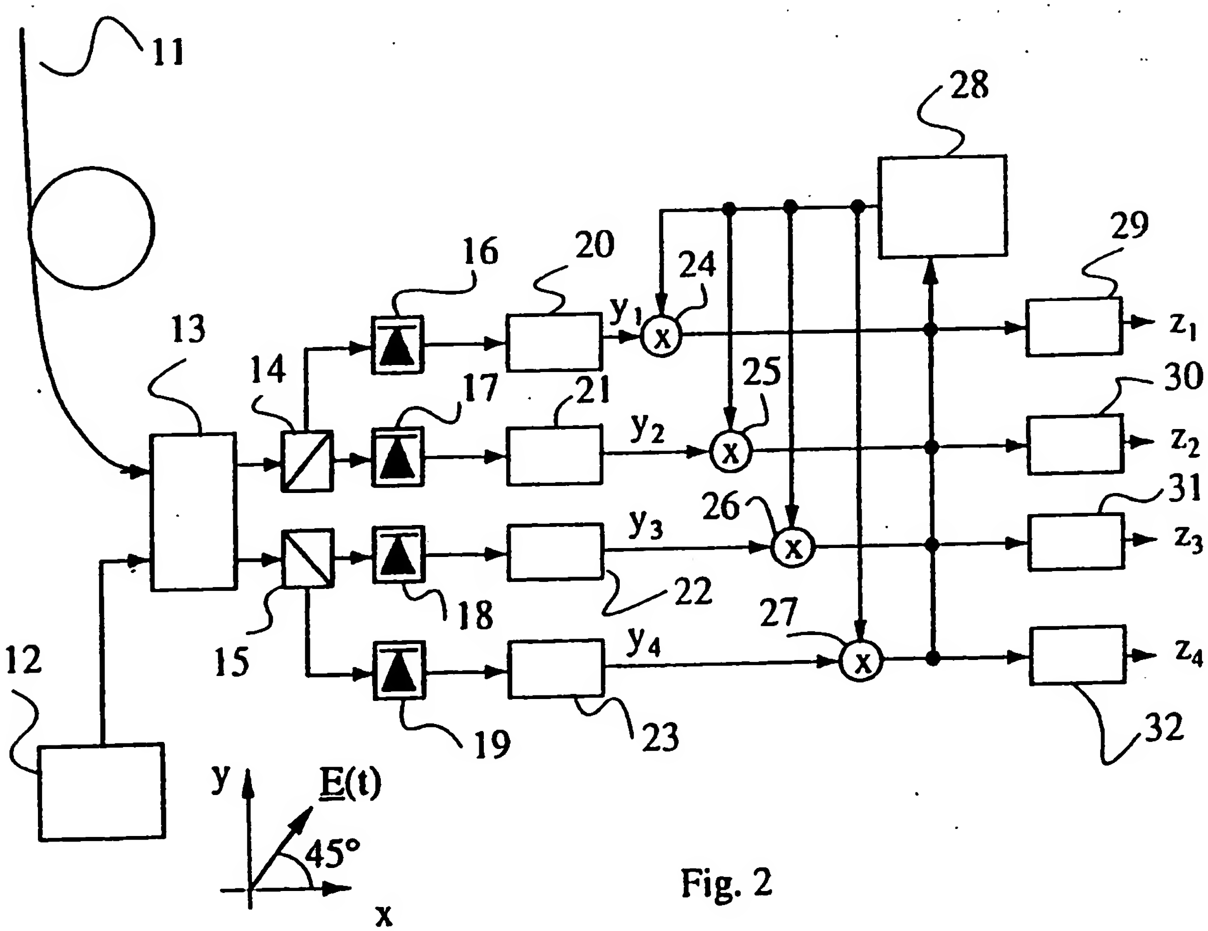
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
y_1
y_2
y_3
y_4
z_1
z_2
z_3
z_4
y
x
E(t)
45°

Fig. 2

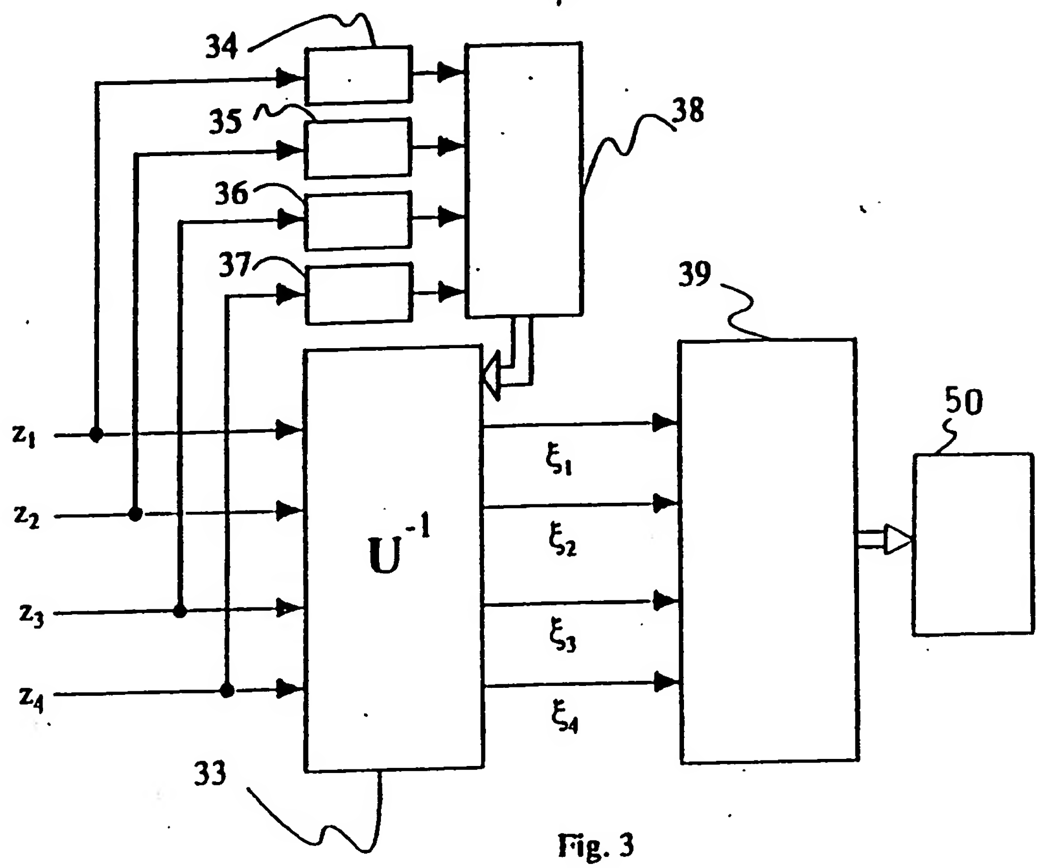
34
35
36
37
38
39
50
z_1
z_2
z_3
z_4
U^{-1}
ξ_1
ξ_2
ξ_3
ξ_4
33

Fig. 3

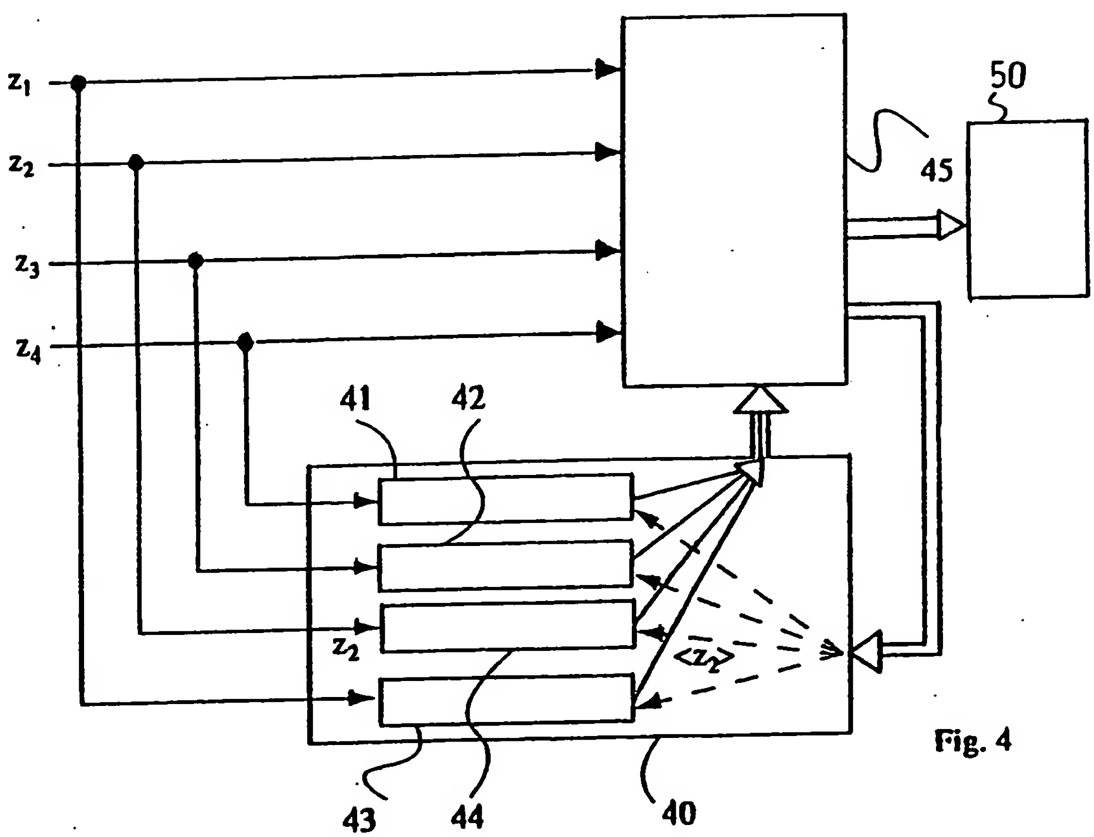
z_1
z_2
z_3
z_4
50
45
41
42
z_2
$\langle z_2 \rangle$
43
44
40

Fig. 4

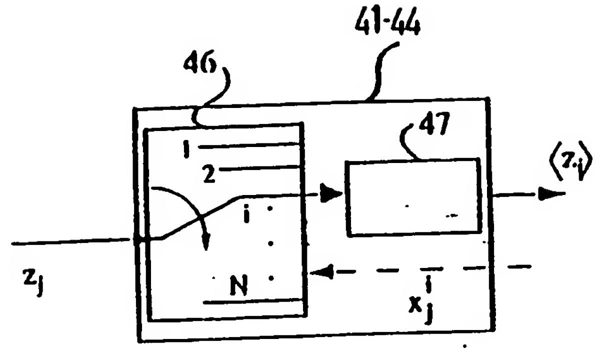
41-44
46
47
1
2
i
N
$\langle z_j \rangle$
z_j
x_j^i

Fig. 5

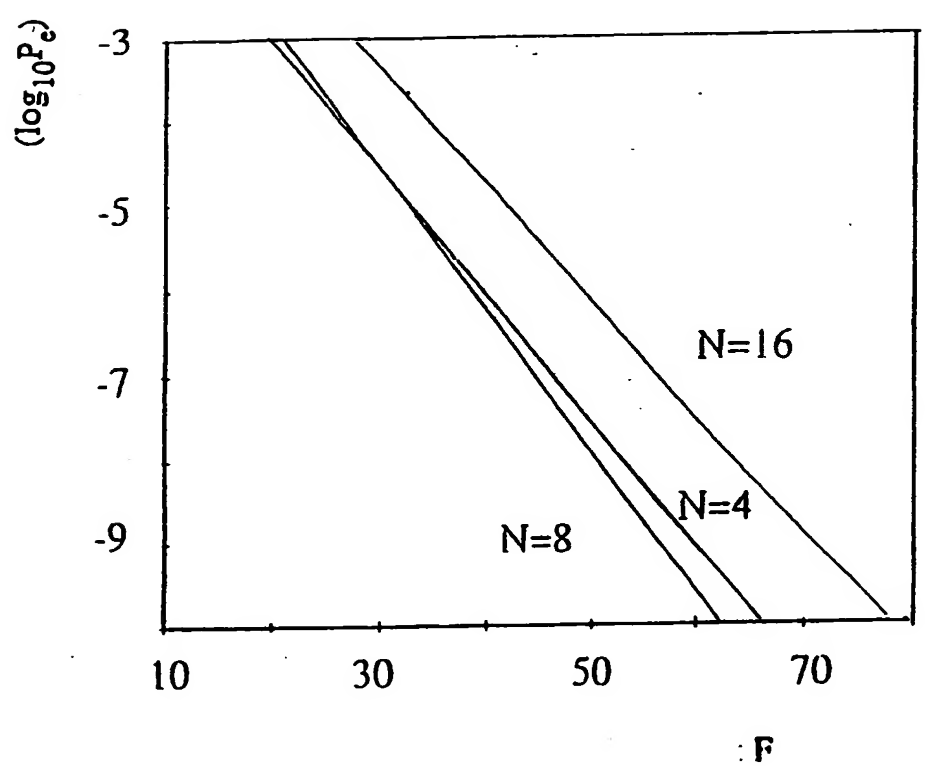
$(\log_{10} P_e)$
-3
-5
-7
-9
N=16
N=4
N=8
10
30
50
70
F

Fig. 6

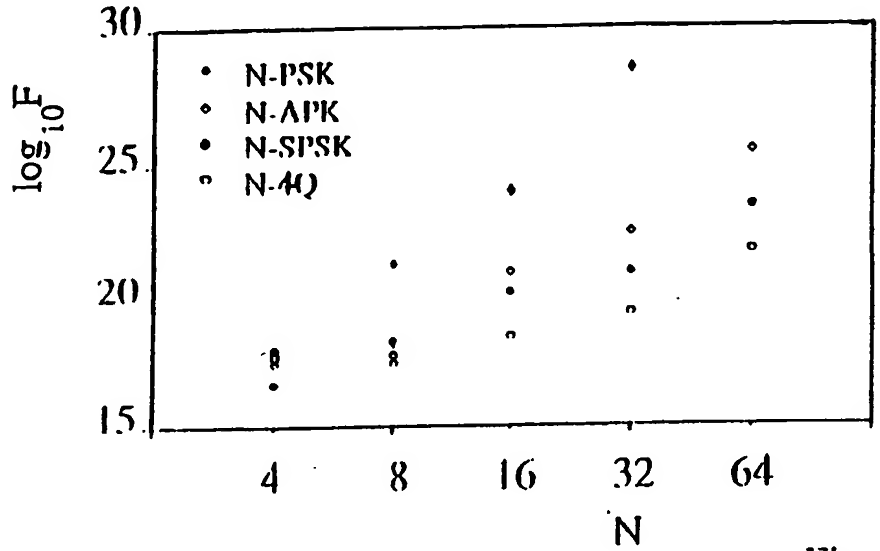
30
25
20
15
$\log_{10} F$
N-PSK
N-APK
N-SPSK
N-4Q
4
8
16
32
64
N

Fig. 7

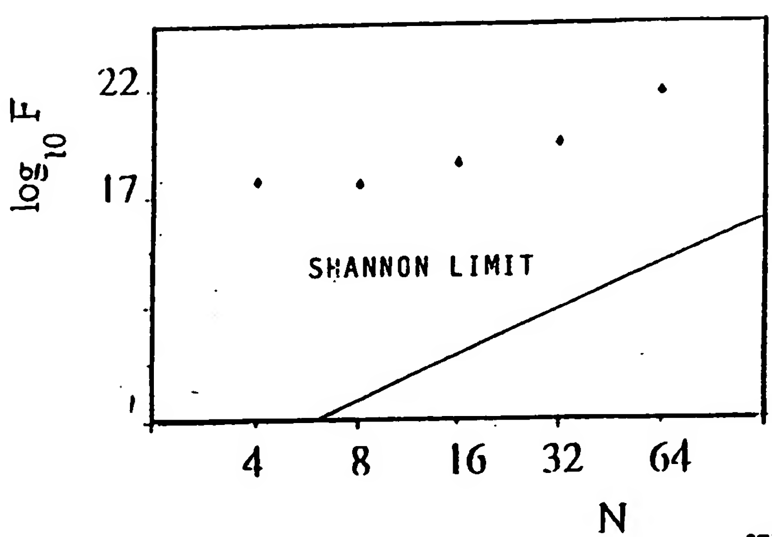
22
17
$\log_{10} F$
SHANNON LIMIT
4
8
16
32
64
N

Fig. 8

INTERNATIONAL SEARCH REPORT

International Application No PCT/IT 91/00036

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int.Cl. 5 H04B10/12 ; H04B10/14

II. FIELDS SEARCHED

Minimum Documentation Searched[7]

Classification System	Classification Symbols
Int.Cl. 5	H04B ; H04L

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched[8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]

Category °	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No.[13]
A	EP,A,277 427 (BRITISH TELECOMM.) August 10, 1988 see page 7, line 40 - line 56 see page 10, line 19 - line 46; claims 1-3; figures 4,9,10 ---	1,2,4,5
A	US,A,3 752 992 (FLUHR) August 14, 1973 see column 1, line 56 - column 2, line 10 see column 2, line 38 - column 3, line 33 ---	1,2,4,5
A	ELECTRONICS LETTERS vol. 26, no. 4, February 15, 1990, STEVENAGE,GB pages 244 - 246; BENEDETTI ET AL.: 'Performance evaluation of multilevel polarisation shift keying modulation schemes ' see the whole document ---	3

-/--

° Special categories of cited documents : [10]

"A" document defining the general state of the art which is not considered to be of particular relevance

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
02 AUGUST 1991	30.08.91
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	WAGNER U.

1

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)		
Category °	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No.
A	EP,A,280 075 (SIEMENS) August 31, 1988 see column 1, line 1 - column 3, line 54 see column 4, line 20 - column 5, line 39 ---	6

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL PATENT APPLICATION NO.

IT 9100036
SA 47142

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The members are as contained in the European Patent Office EDP file on
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02/08/91

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP-A-277427	10-08-88	AU-B- 598619	28-06-90
		AU-A- 8305987	30-06-88
		JP-A- 63174435	18-07-88
US-A-3752992	14-08-73	None	
EP-A-280075	31-08-88	None	

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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82